Imaging challenges in optical tomography

Dutch Inverse Problems, November 26st 2021

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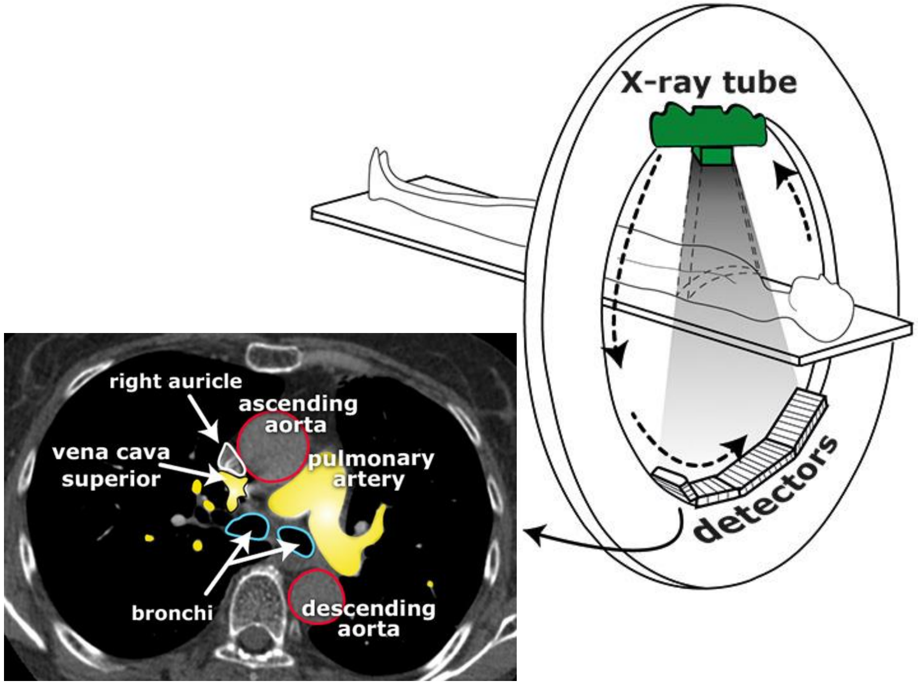
ImPhys
Image to insight
Insight in imaging
Department of Imaging Physics

TU Delft

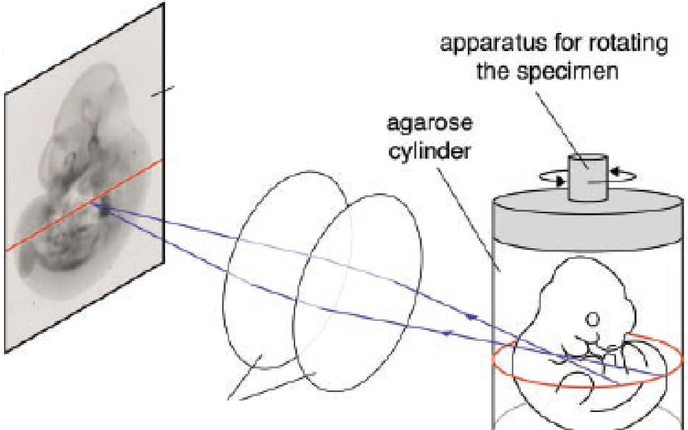
Optical versus X-ray tomography

X-ray tomography

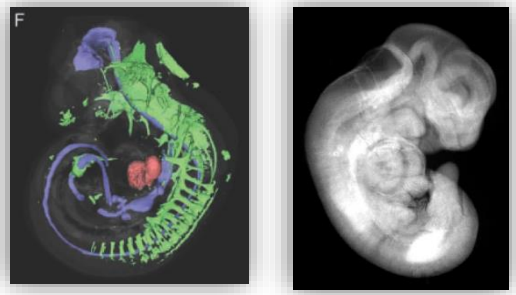


https://www.startradiology.com/the-basics/x-rayct-technique/index.html

Optical tomography



Optical imaging system



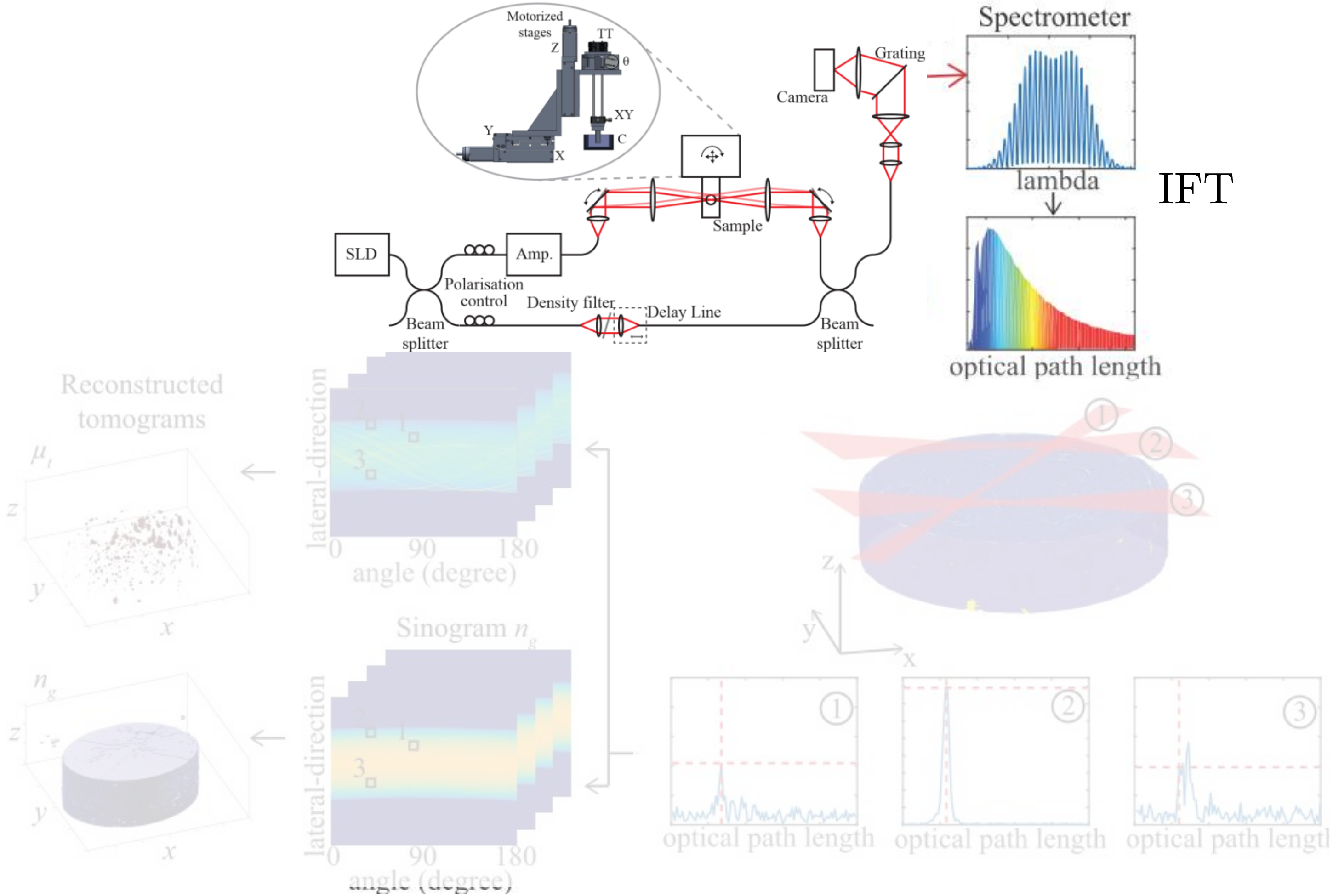
Images from: Sharpe et al. Science 296, 541 (2002)

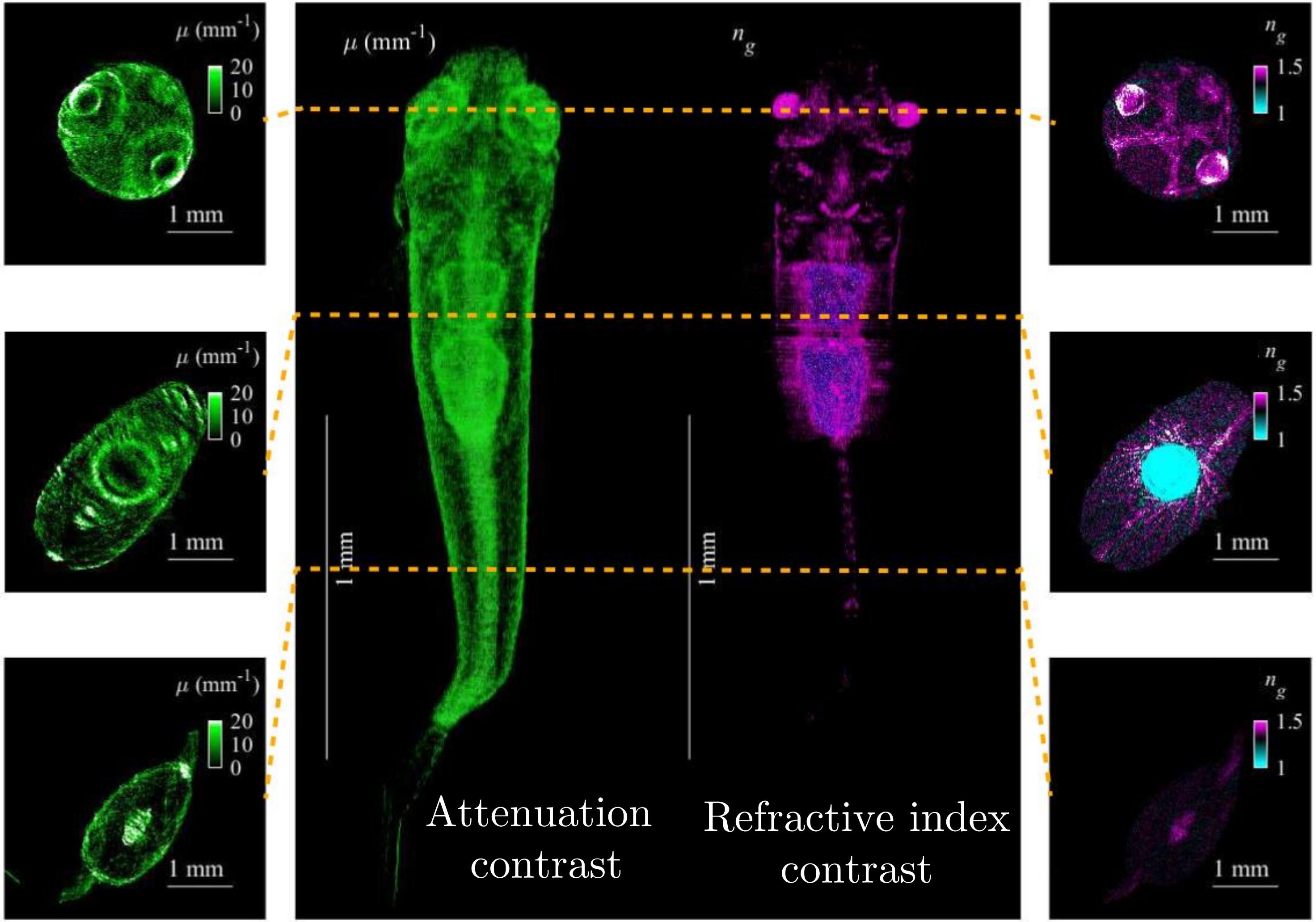
Challenges in optical tomography

Scattering

Diffraction

Optical coherence projection tomography



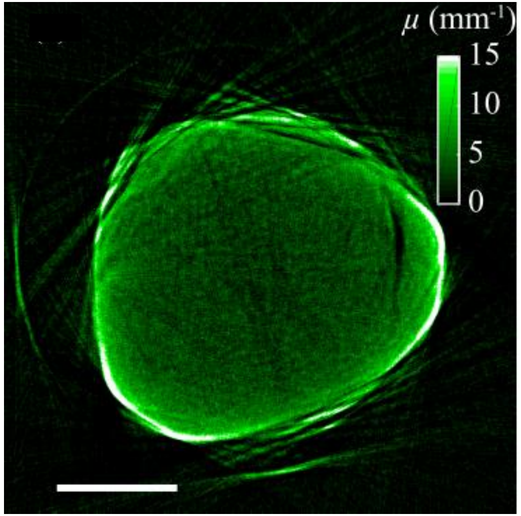

μ (mm-1)
20
10
0
1 mm
μ (mm-1)
20
10
0
1 mm
μ (mm-1)
20
10
0
1 mm
μ (mm-1)
n g
1 mm
1 mm
Attenuation contrast
Refractive index contrast
n g
1.5
1
1 mm
n g
1.5
1
1 mm
n g
1.5
1
1 mm

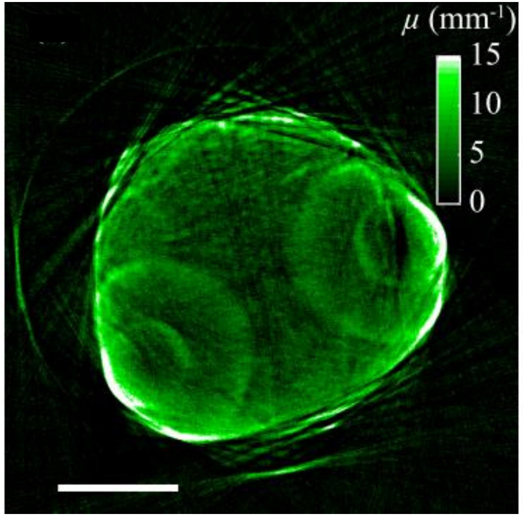
OCPT imaging depth analysis

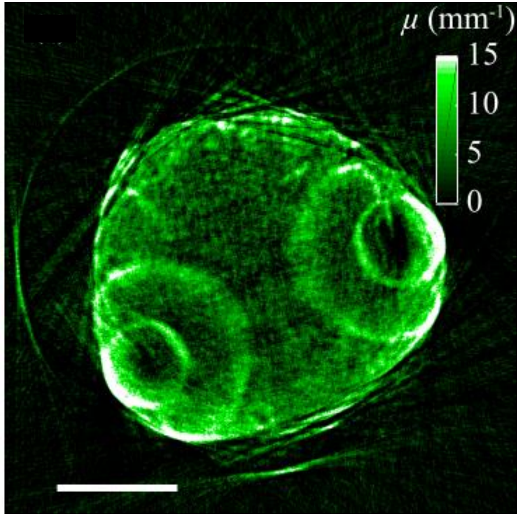
Confocal

Confocal & coherence

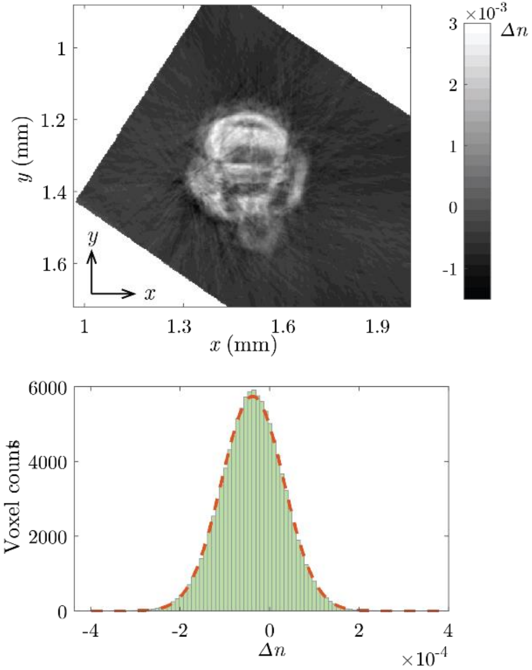
Full OCPT imaging







Optical tomography: scattering



$$\Delta n = 8 \cdot 10^{-5}$$

H. Hama et al., Nature Neuroscience 14, 1481 (2011)

Large scale high sensitivity optical diffraction, tomography of zebrafish, J. van Rooij and J. Kalkman, Biomed. Opt. Express 2019

Challenges in optical tomography

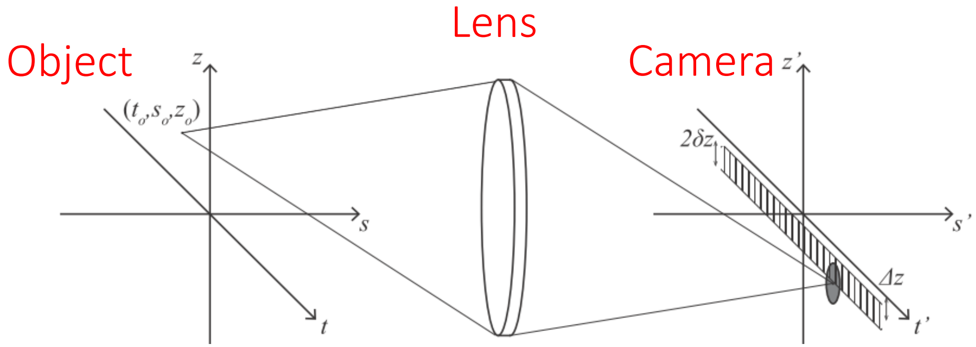
Scattering

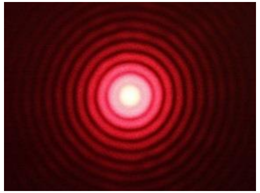
Diffraction

The (optical) depth of focus problem

Objects in focus are sharp, objects out of focus are blurred

Image resolution in optical tomography (I)



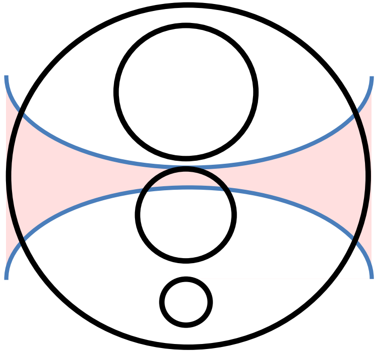


$$p(t',\cancel{z'}) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(t'-t, s'-s, \cancel{z'-z})|h(t,s,z)|^2 \mathrm{d}t\mathrm{d}s\cancel{\mathrm{d}z}\Big|_{s'=0}$$

Approximation:

Slide thickness > PSF width

Convolution is integration over the object emission

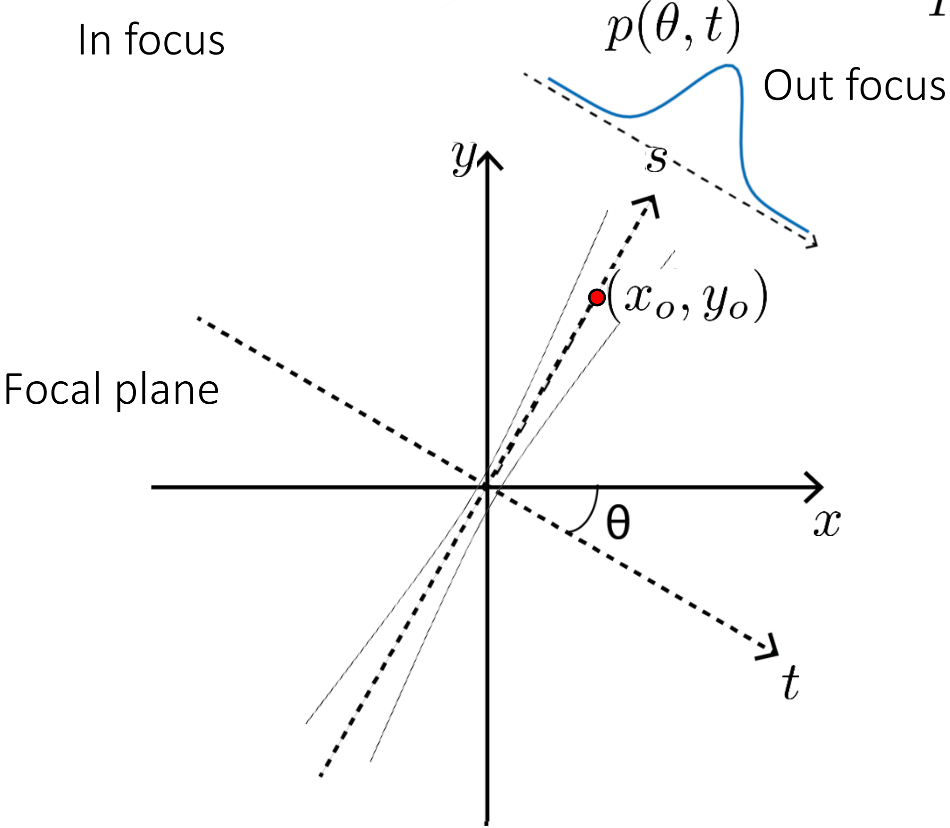


Gaussian beam PSF

Image resolution in optical tomography (II)

Projection slice theorem:

$$FT_{1D}\{proj\{f\}\} = slice\{FT_{2D}\{f\}\}$$



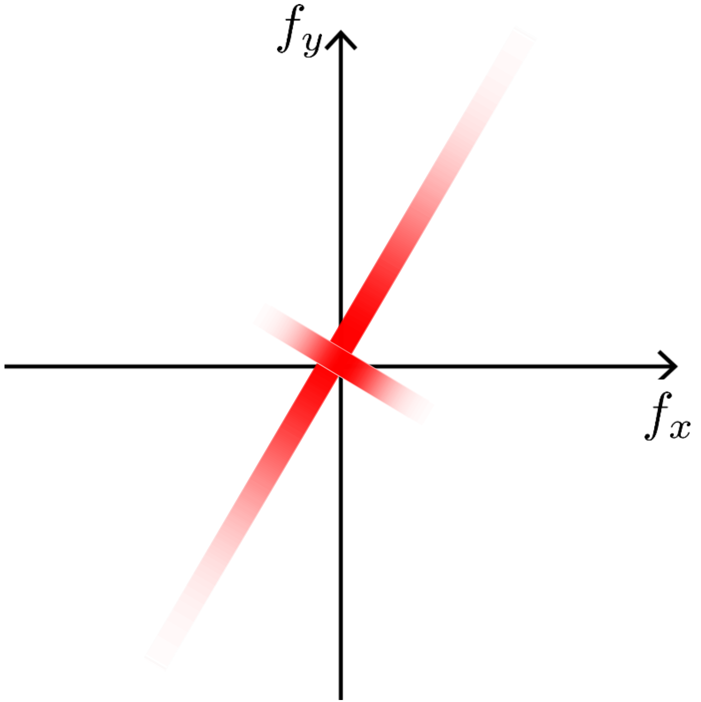
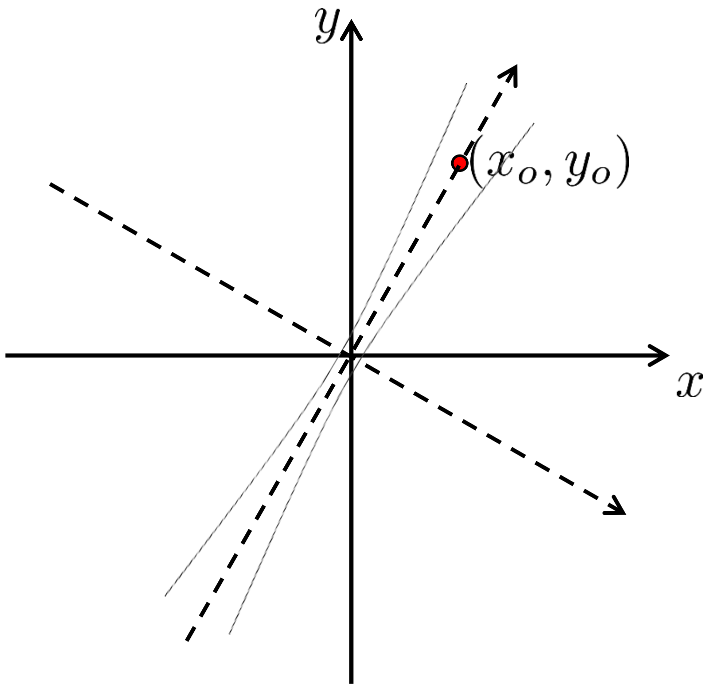


Image resolution in optical tomography (III)



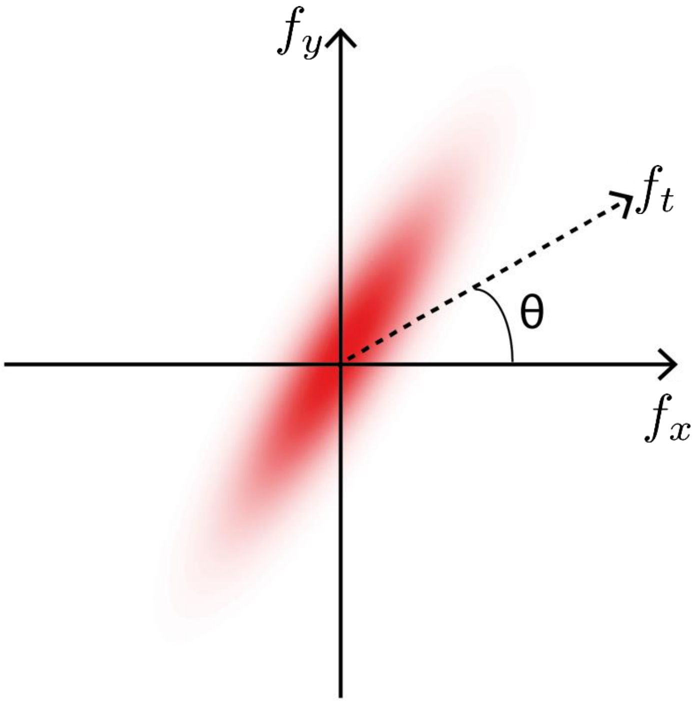


Image resolution in optical tomography (IV)

$$I_t(f_x, f_y) = \exp\left(-\frac{1}{2}\pi^2(f_x^2 + f_y^2)\left[w_0^2 + \frac{\lambda^2 r_i^2 \sin^2(\theta_i - \theta)}{\pi^2 w_0^2}\right]\right)\exp\left(-2\pi i\left(x_i f_x + y_i f_y\right)\right)$$

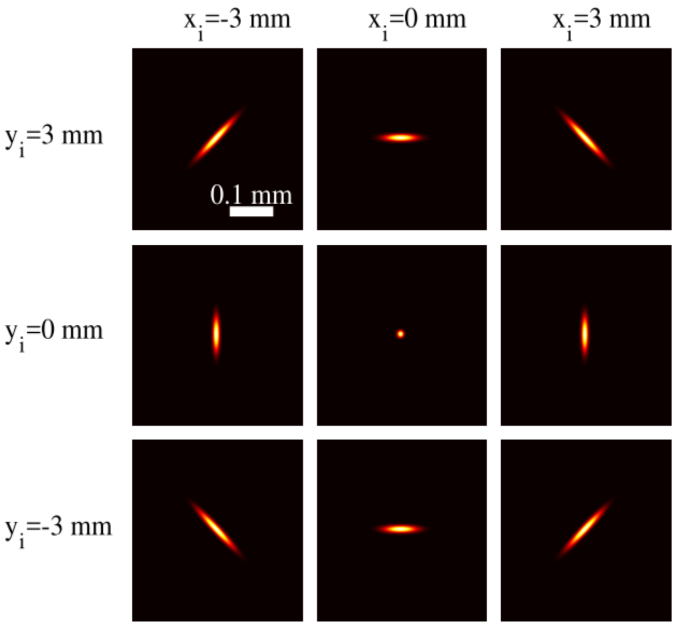
Fourier transform of $I_t(f_x, f_y)$ is point spread function

$$PSF(u,v) = \sqrt{\frac{4}{\pi^2 w_0^2\left(w_0^2 + \frac{\lambda^2 r_i^2}{\pi^2 w_0^2}\right)}}\exp\left(-\left[\frac{2u^2}{w_0^2} + \frac{2v^2}{\left(w_0^2 + \frac{\lambda^2 r_i^2}{\pi^2 w_0^2}\right)}\right]\right)$$

- reduction of impulse response in radial direction
- PSF width is independent of radial direction
- tangential PSF widens with increasing radial direction

Image resolution in optical tomography (V)

w_0=10 μm
$\lambda = 545$ nm
NA $= 0.04$



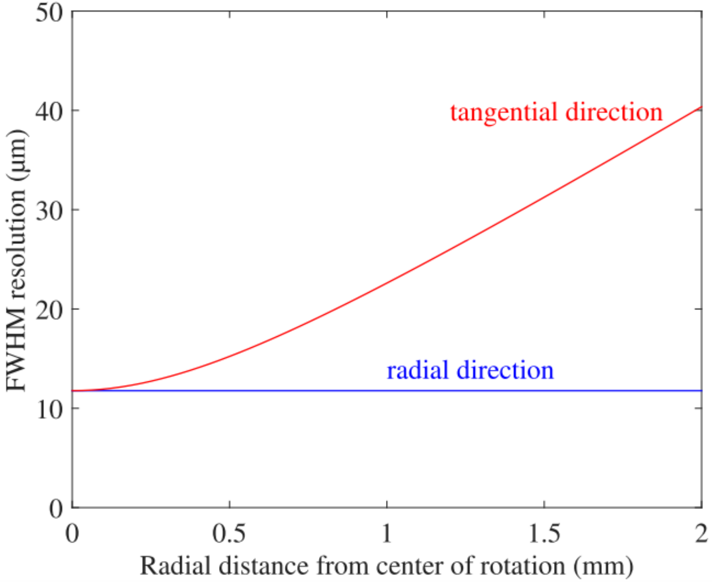


Image resolution in optical tomography (VI)

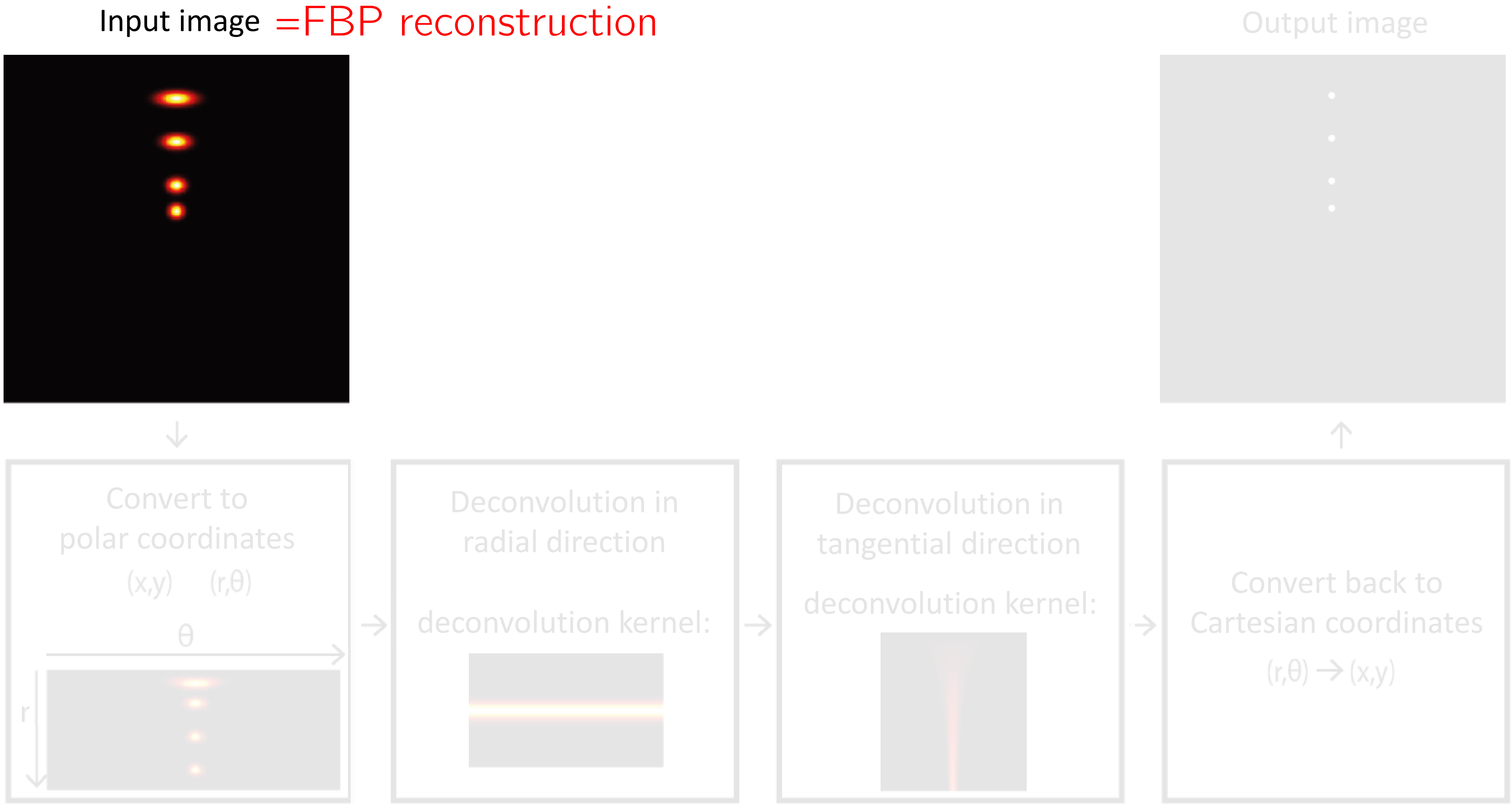


Image resolution characterization

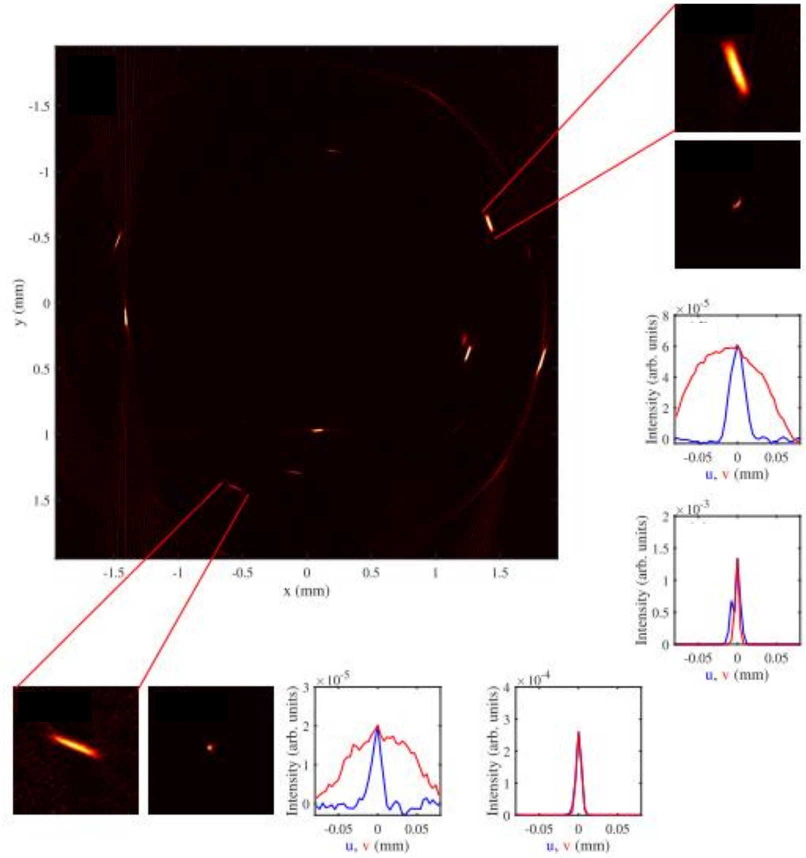
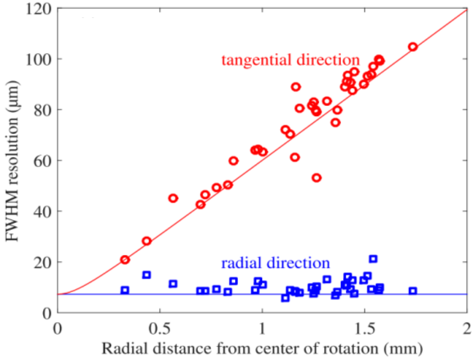


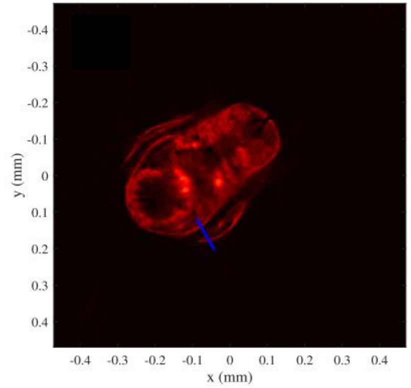
Image resolution and deconvolution

Fluorescent beads

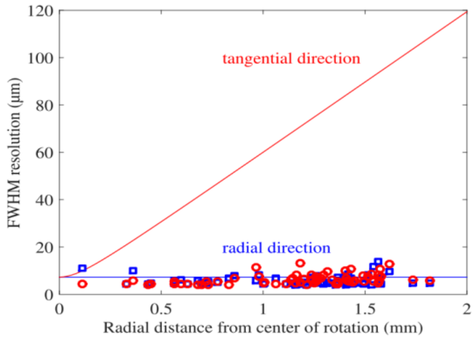
Zebrafish

Filtered backprojection





FBP
+
convolution



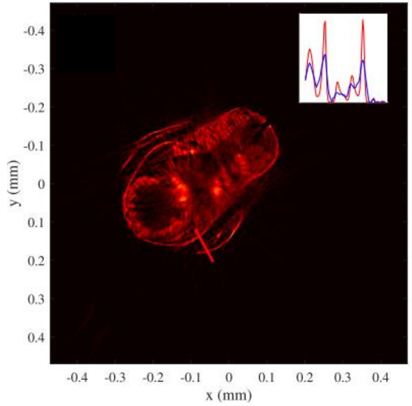


Image resolution and deconvolution in optical tomography, J. van der Horst and J. Kalkman, Optics Express 24, 24460 (2016)

Iterative tomographic reconstruction

Problem definition

$$p(s,\theta) = \int \underbrace{f[(x-s)\cos(\theta) + z\sin(\theta), (x-s)\cos(\theta) - z\sin(\theta)]}_{\text{Object (shifted and rotated)}} \overbrace{|h(x,z)|^2}^{\text{Point spread function}} \mathrm{d}x\mathrm{d}z$$

Discretization

$$\mathbf{p} = \mathbf{A} \cdot \mathbf{f}$$

$\mathbf{p} \in \mathbb{R}^{m \cdot n \times 1}$ Vector of stacked projections

$\mathbf{f} \in \mathbb{R}^{n \cdot n \times 1}$ Vector of the object

$\mathbf{A} \in \mathbb{R}^{m \cdot n \times n \cdot n}$ Geometry matrix (size of the object x the number of angles)

Optimization

Measurement geometry

Object

Projection data

$$\min_{\mathbf{f}} \quad \frac{1}{2}\|\mathbf{A} \cdot \mathbf{f} - \mathbf{p}\|_2^2$$

Iterative tomographic reconstruction

1000x1000 grid points in the object plane, 360 projections (1 per degree)

⇩

Projection data $\mathbf{p}$ has size (360x1000)x1

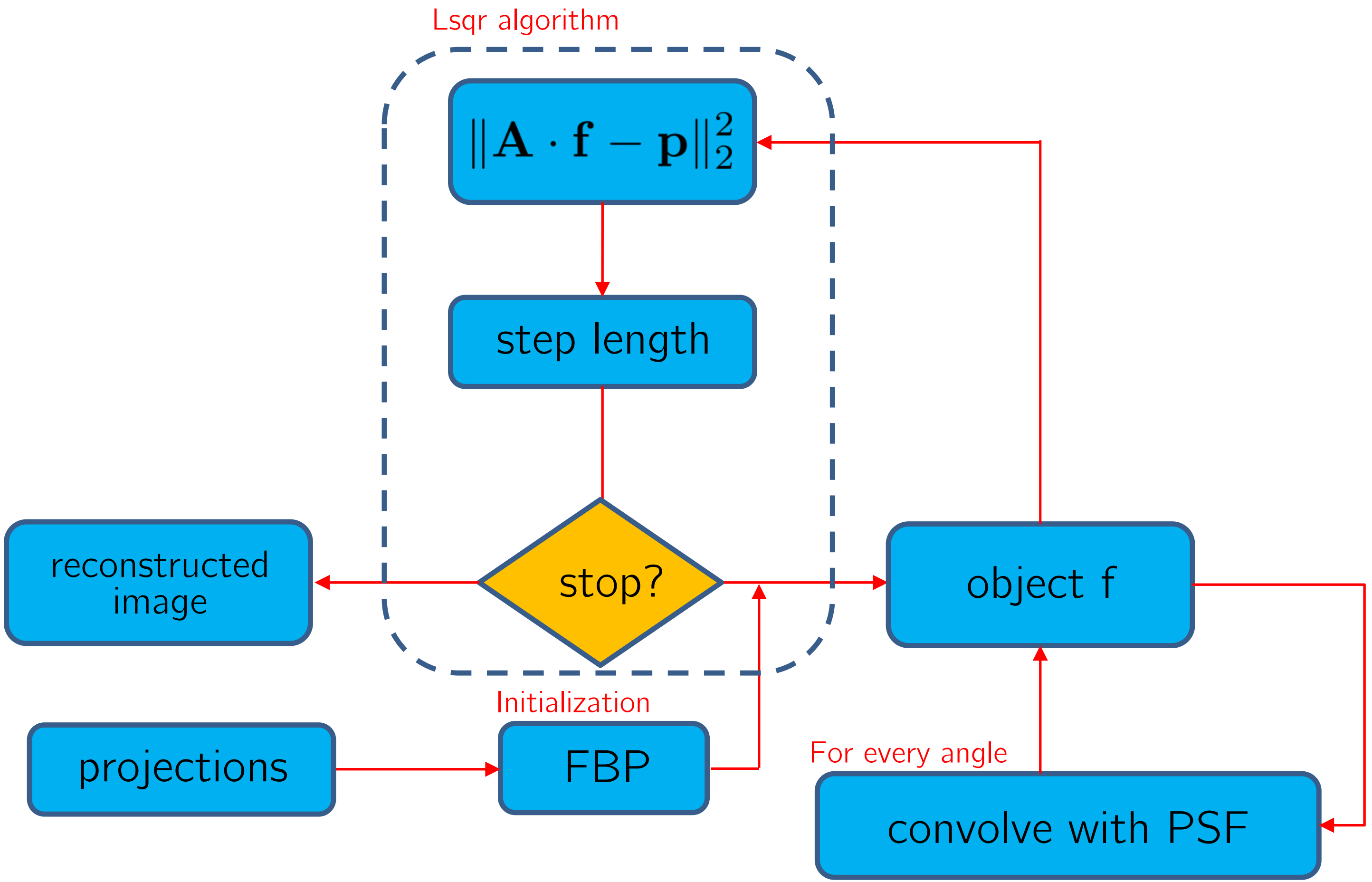
Object $\mathbf{f}$ has size (1000x1000)x1

Measurement geometry $\mathbf{A}$ has size (360x1000)x(1000x1000) ≈8 terabyte

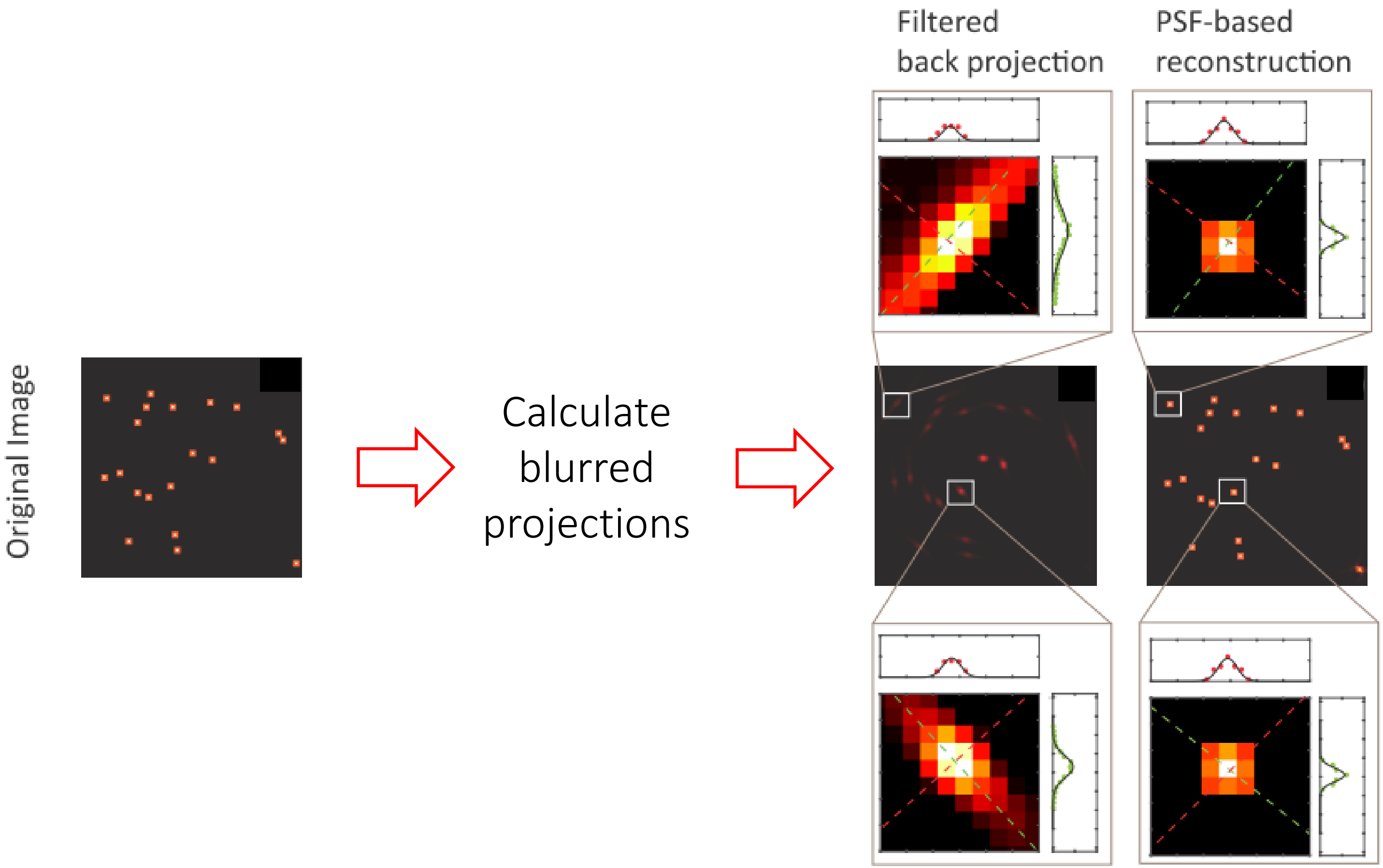
Solution

Calculate for every angle and lateral offset the difference $\|\mathbf{A} \cdot \mathbf{f} - \mathbf{p}\|_2^2$
and calculate the total merit value sequentially

Iterative reconstruction algorithm

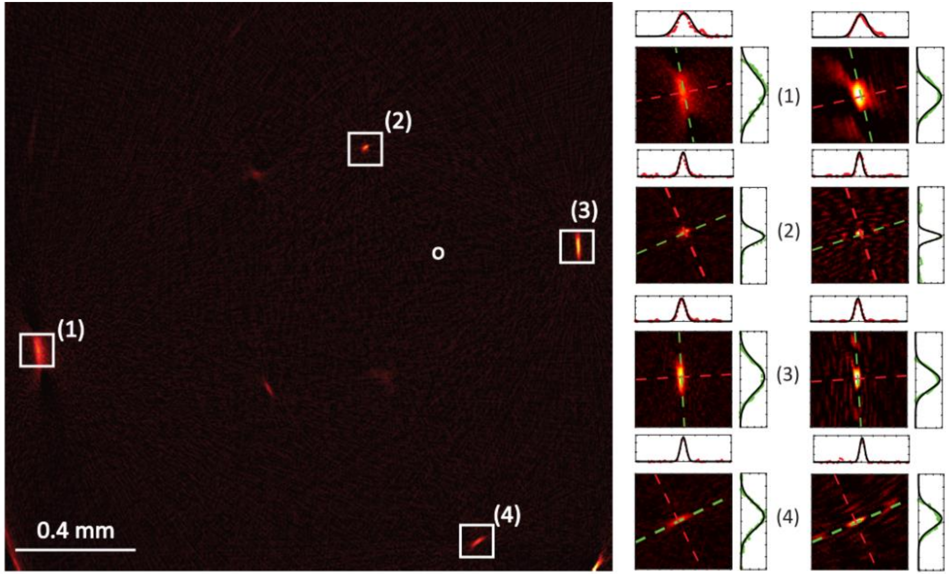


Optical tomographic reconstruction

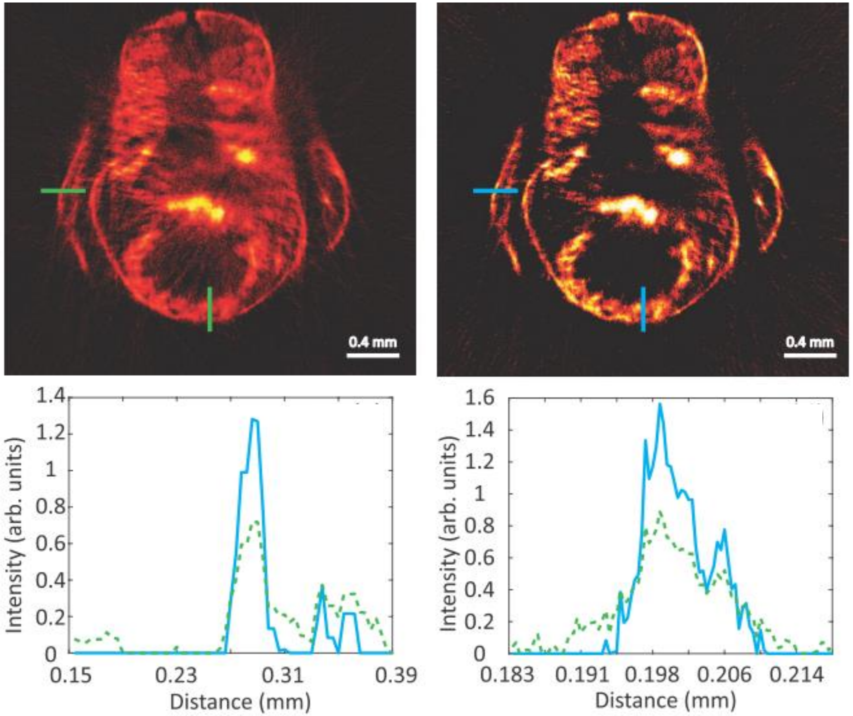


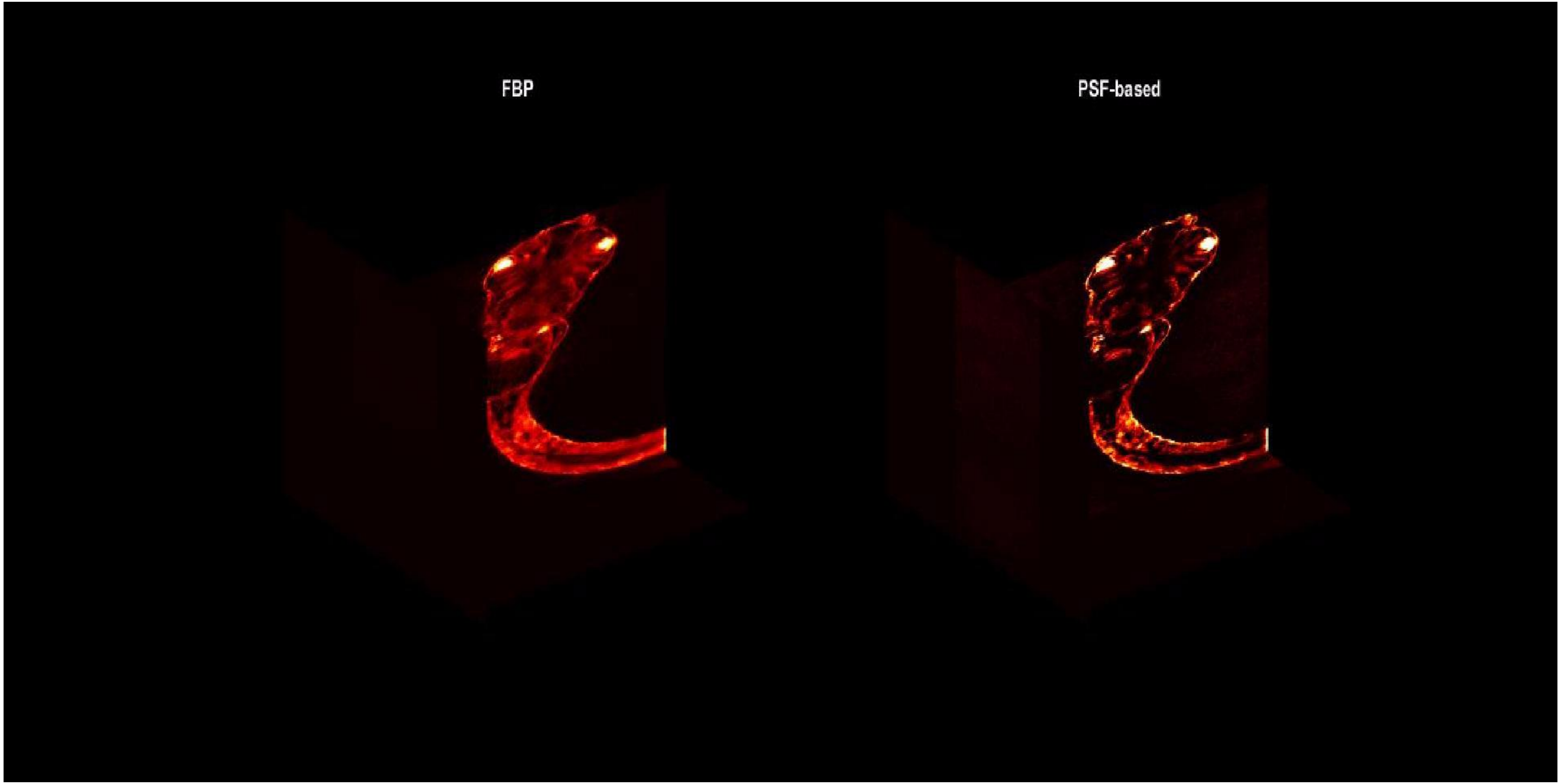
Optical tomographic reconstruction

Fluorescent beads



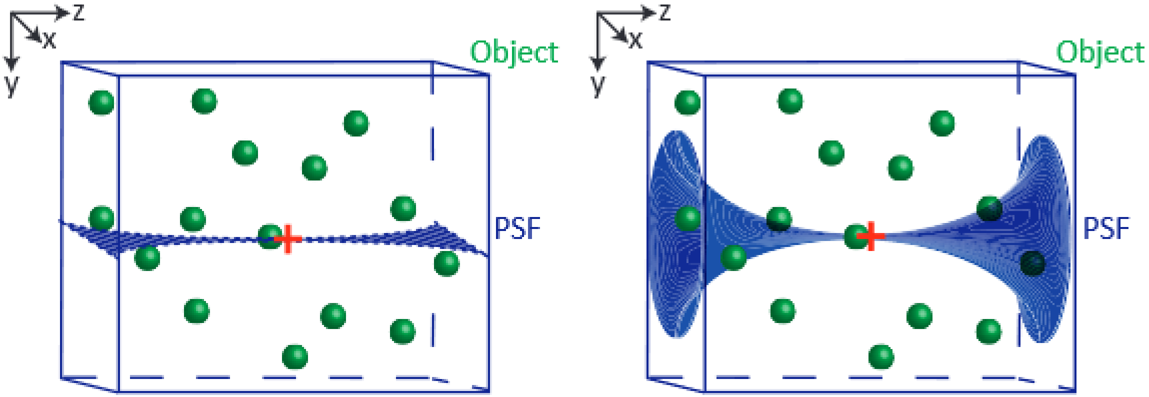
Zebrafish

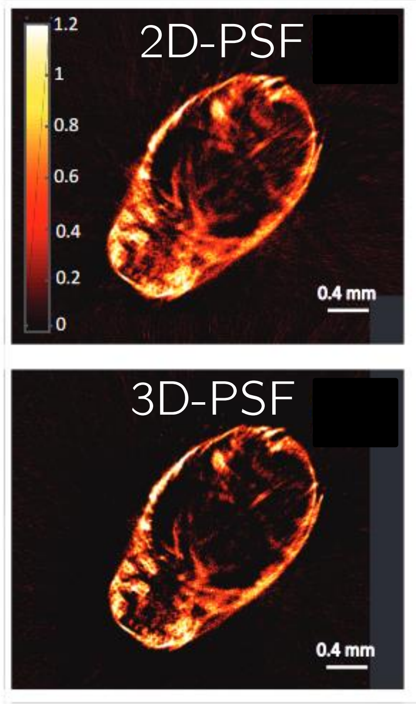




Point spread function based image reconstruction in optical projection tomography
A. K. Trull, J. van der Horst, W. J. Palenstijn, L. J. van Vliet, T. van Leeuwen, and J. Kalkman, Physics in Medicine and Biology 62, 7784 (2017)

The 3D problem reconstruction problem





Projection data $\mathbf{p}$ has size (360x950x300)x1

Object $\mathbf{f}$ has size (950x950x300)x1

Measurement geometry $\mathbf{A}$ has size (360x950x300)x(950x950x300)

Summary and outlook

- Effects of diffraction in optical tomography can be compensated for
- Deconvolution approach is fast and gives best results for point objects
- PSF-based reconstruction is slower, but gives best results for extended objects

Future work

- Full 3D reconstruction
  - ✓ Fast & iterative gigavoxel reconstruction (non-separable)

- Multi-modal reconstruction
  - ✓ fluorescence + phase

- Multi-physics reconstruction
  - ✓ including beam propagation in the sample (refraction, diffraction)
  - ✓ including polarization